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Hydraulic model study of the blowback behaviour of the bottom outlet of the Berg River Dam, South Africa

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The Berg River Dam is equipped with the first multi-level draw-off environmental flood release outlet in South Africa and can release flows up to about 200 m³/s. The outlet is controlled by a radial gate at the outlet end, and is protected by a vertical emergency gate near the inlet end. Commissioning tests of the emergency gate in 2008 found that large volumes of air were expelled, instead of the expected air entrainment into the air vent, designed to reduce expected negative pressures in the conduit during emergency gate closure.

This paper describes the testing of a 1:14 physical model representing the outlet works of the Berg River Dam to determine the reasons for the unexpected release of air from the outlet work's air vent, as observed in the field during the commissioning tests of the emergency gate in the outlet conduit.

Simulations of continuous gate closure on the as-built physical model of the Berg River Dam outlet showed predominant inflow of air into the air vent during emergency gate closure, with intermittent short duration high-speed air releases during the stages of emergency gate openings between 37% and 25% open. The problem was determined to be one of intermittent air blowback from the outlet conduit via the air vent during the latter stage, rather than continuous air release for all stages of the gate opening operation. The cause of the blowback was found to be the constriction of flow due to a reduction in the conduit cross-section at the radial gate chamber located at the downstream end of the outlet conduit.

INTRODUCTION

Berg River Dam

The Berg River Dam (Figure 1) is located 6 km west of Franschhoek, and the supplement scheme is located approximately 10 km downstream of the dam. The dam is a concrete-faced rockfill embankment, approximately 65 m high and 990 m wide, and has a base width of 220 m. It has a gross storage capacity of 130 million m³ (TCTA 2008). It is the first of its kind in South Africa, comprising structures that permit the release of both low and high

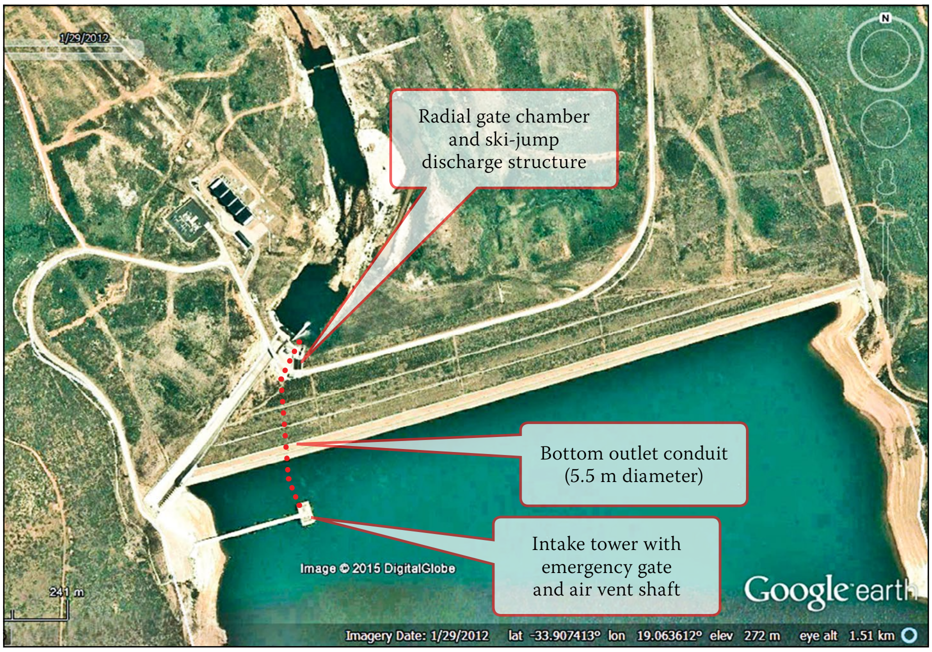

Figure 1 Berg River Dam wall with location of bottom outlet (Google Earth photograph)

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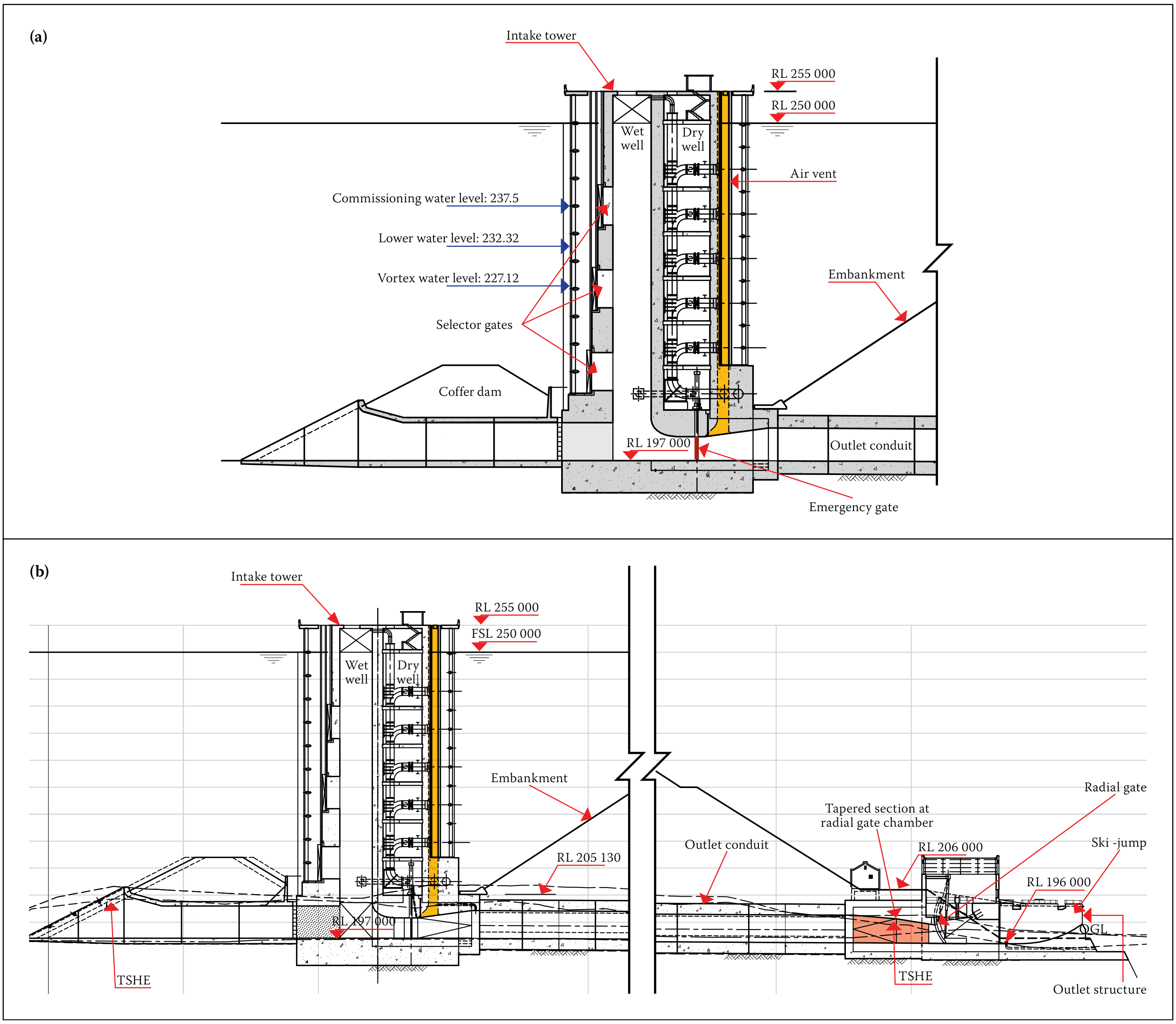

Figure 2 (a) Cross-section of Berg River Dam intake tower and (b) complete outlet structure (adapted from TCTA 2003)

environmental flood releases, the latter up to 200 m^3/s. The outflow for the environmental flood release is controlled by a radial gate at the end of the outlet conduit and is protected by a vertical emergency gate near the inlet of the conduit (Figure 2).

Background to the problem

A trial closure of the emergency gate in the outlet conduit of the Berg River Dam was undertaken by the TCTA on 12 June 2008, as shown in Figure 3. During the commissioning test the water level in the dam was 237.5 masl, the discharge through the conduit was 201 m^3/s as measured in the field, and the emergency gate in the conduit was closed from 100% open to 0% in 20 minutes (Shand 2008). The outlet conduit design included an air vent downstream of the emergency gate with the purpose to introduce air downstream of the gate to counteract the negative pressures that were expected in the conduit during

Figure 3 Commissioning test of the Berg River Dam (Photo: *Civil Engineering*, August 2008, p 49)

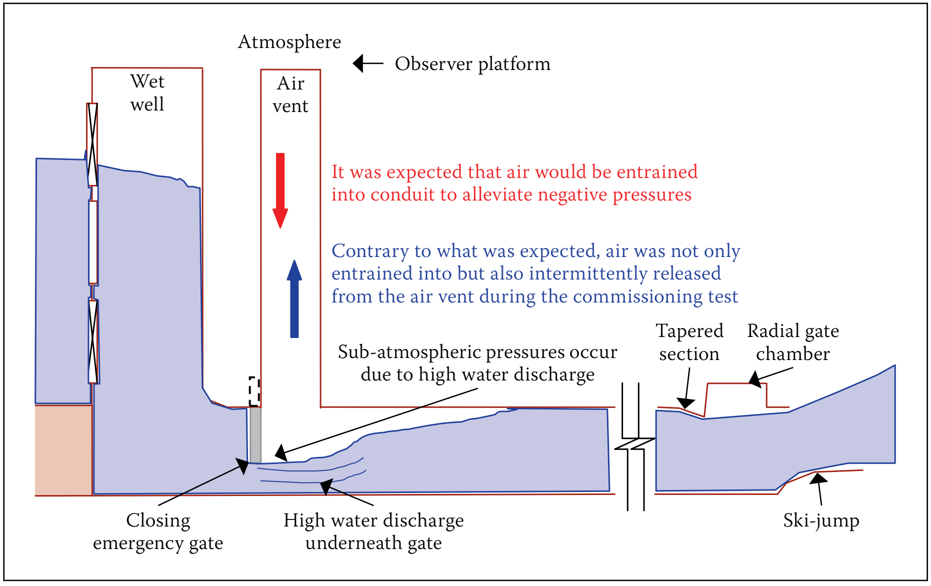

Figure 4 Outlet conduit configuration

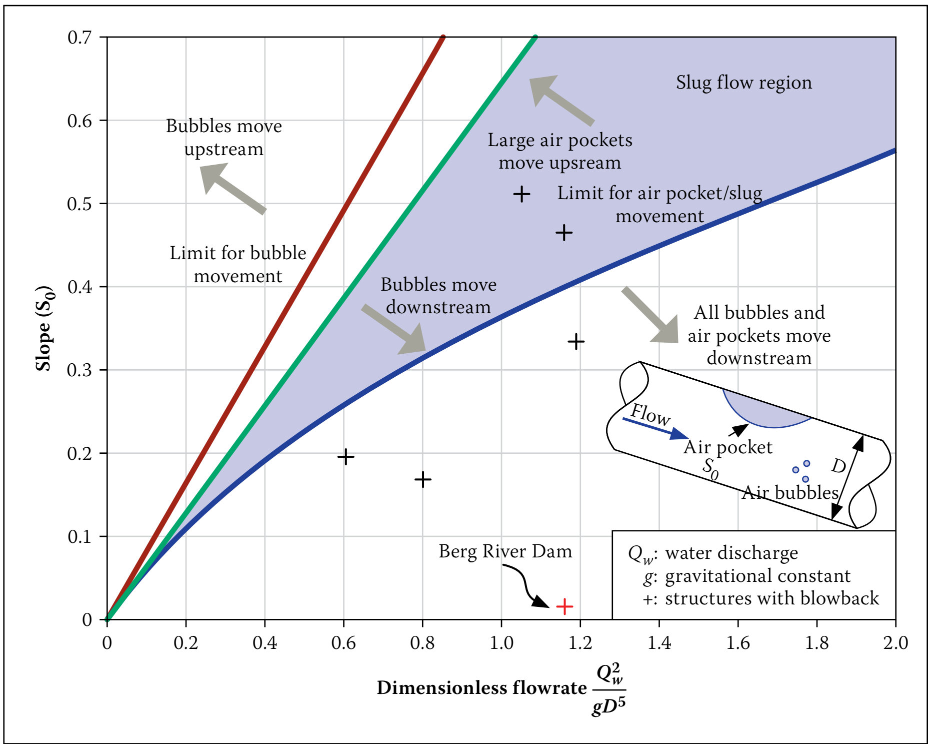

Figure 5 Bubble motion in closed conduits flowing full (adapted from Falvey 1980)

emergency gate operations. Contrary to the theoretical design, the field measurement of air velocities in the air shaft indicated that, while the emergency gate was closing, very large volumes of air were being released from the 1.8 m^2 air shaft, commencing when the gate was about 30% closed (Figure 4). The latter observed air release was so severe that the heavy steel grating cover on the inlet end of the air vent shaft was blown off, which nearly caused serious injury to personnel who were measuring air velocities there.

As part of a South African Water Research Commission project (WRC 2012), co-funded by the TCTA, the Stellenbosch University constructed a 1:14.066 (undistorted scale) physical model of the relevant bottom outlet works of the Berg River Dam to evaluate the two-phase flow phenomenon in the outlet works.

Objectives of the model study

The objectives of the model study were as follows:

1. To determine reasons for the release of large volumes of air flow in the air vent, as observed during the commissioning closure test of the emergency gate on 12 June 2008.
2. To provide a solution to mitigate the observed excessive air release from the air vent, since air release of the intensity as was observed in the commissioning test may cause structural damage, as well as injury to personnel.

LITERATURE

Air blowback phenomenon

Prototype cases in which air blowback (large air pockets moving against flow) occurred was investigated by Sailer (Falvey 1980). Figure 5 indicates the air reverse flow region. The five prototype structures that experienced air blowbacks are indicated by a plus (+). Two of these blowback cases lay within the blowback zone at design discharge, i.e. valve openings at 100% open. The other three cases had to pass through the blowback zone when the flow is reduced from the design discharge, which means that these three cases would experience blowback at valve openings smaller than 100%, since with smaller valve openings these three "+"-plot locations would move to the left on the graph until they cross the line marked "Limit for air pocket/slug movement" (Falvey 1980).

The literature review indicated that explosive blowback incidents occurred on numerous overseas high-head conduit schemes. Lowe (1944) described the air blowback phenomenon which occurred on the Owyhee Dam in Oregon, USA. The long-section of the dam showed that the horizontal conduit ends in a stilling basin. Wave action was experienced in the stilling basin, which sealed the exit of the outlet conduit for short periods. The intake air was compressed when the conduit outlet was choked by the waves. This resulted in the compressed air being released both downstream and upstream – the latter was called the blowback of the compressed air. There are similarities between this case study and the Berg River Dam in the basic mechanism that causes air blowback (the Berg River Dam has a constriction for the radial gate chamber at the outlet end of the conduit, since the ceiling of the conduit slopes downwards in order to house the radial gate (see Figure 7)).

The US Army Corps of Engineering (USACE 1980) developed a guideline manual for the design of tunnel-conduit type outlets, based on model tests and prototype data. This manual recommends that the elevation of the hydraulic grade line (pressure gradient line or water surface) at the conduit exit should be lower than the soffit of the conduit. The flow inside the conduit should therefore be unrestricted to ensure free-flow conditions at the conduit exit. To prevent blowback it is further recommended that flow in a high-head outlet should flow partially full and should never be constricted by any structure or mechanism further downstream in the conduit.

MODEL OF THE BERG RIVER DAM

General
A physical model of the Berg River Dam was constructed to simulate the closure of the emergency gate under similar water levels and intake gate configurations as at the time of the commissioning test in 2008 (Vos 2011). Figure 6 shows a photograph of the model and Figure 7 shows a line sketch of the model layout.

Model scale
The model of the Berg River Dam was designed to a 1:14.066 undistorted scale. The odd scale of the model was determined by the inside diameter of the available perspex pipe that was used to model the outlet conduit.

Since it was considered that gravitational and inertial forces would dominate in the model, the Froude scale (Webber 1971) was adopted, which implies an undistorted model.

Measuring equipment and techniques

Pressure measurements
Eight S-10 type pressure transducers were used to measure the static pressures and pressure fluctuations in the water tank, water shaft and outlet conduit. The locations of the transducers are shown in Figure 8. The transducers had a sample frequency of 20 Hz, with an accuracy of 0.5% over the total pressure range.

Air velocity measurements and direction indicator
The air velocity in the air vent was measured by means of a Lutron hot-wire anemometer, from which the air discharge was calculated. It had a ± 5% accuracy over the total measurement range. The logger sampled at a frequency of 0.8 Hz.

A wind direction indicator was installed in the top section of the air vent, and the configuration was such that it had negligible influence on the air velocity within the air vent. This apparatus had a mechanical flap that would be in a horizontal position if no wind was blowing in the air vent, and would be directed in the direction of the wind if air was entrained into or released from the air vent. The sign convention assumed for the air velocity in the air vent was positive for air entrained into the conduit and negative for air released from the air vent. The wind direction indicator was not accurate for air velocities less than 0.5 m/s (model).

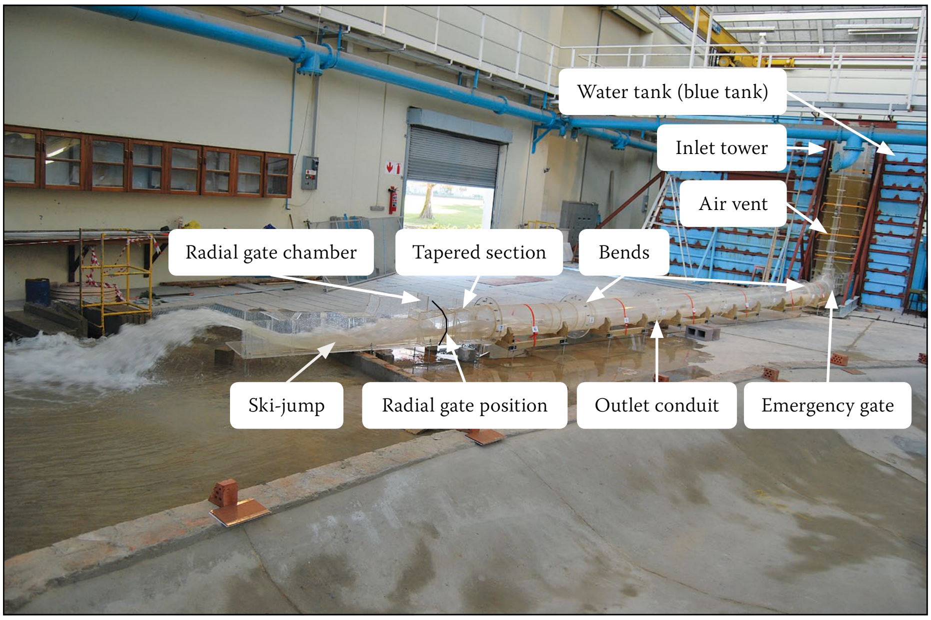

Figure 6 Photograph of physical model

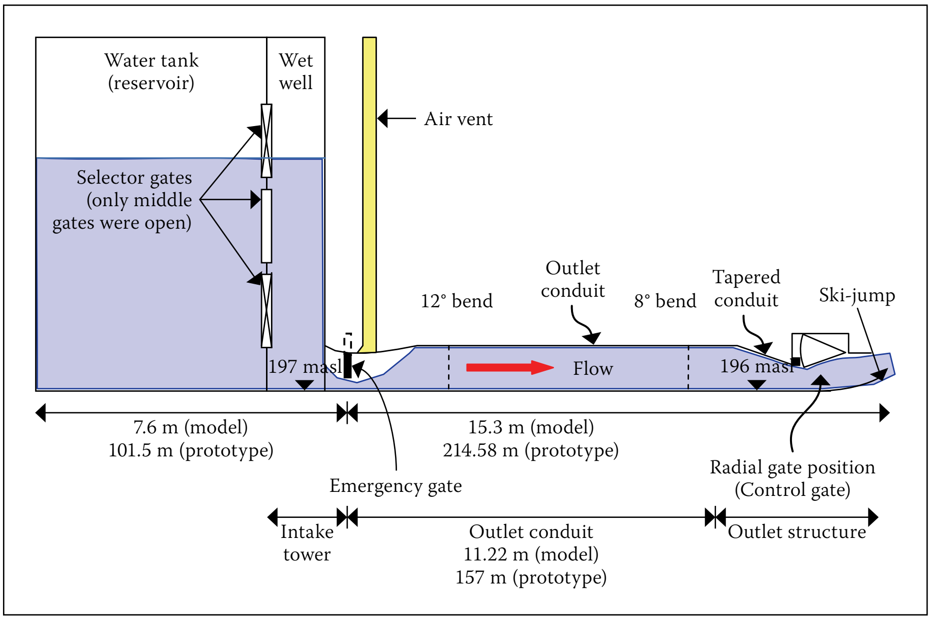

Figure 7 Long-section of the Berg River Dam model (Vos 2011)

Table 1 Emergency gate closure times

Gate closure time number	Emergency gate closure time (prototype) 100% to 0% gate opening	Comment
1	20 min	A 20 min emergency gate closing time used during the **commissioning test of 2008** (Basson 2011).
2	12 min	Designed emergency gate closure time (12 min) according to the **Berg River Dam design report** (TCTA 2003).
3	6 min	Time was chosen to investigate the flow conditions for a **shorter** gate closure time.
4	30 min	Time was chosen to investigate the flow conditions for a **longer** gate closure time.

EXPERIMENTAL PROCEDURE

Experimental controls
An electric motor was used to close the emergency gate in order to obtain the required gate closure time.

The required water flow was obtained by keeping the water level in the tank constant at the water level under evaluation.

The tests were performed with the radial gate fully open, as the emergency gate was designed to be used when the radial gate fails to close.

Transient gate opening simulations

Tests were conducted on the model with its configuration according to the as-built drawings. The air flow in the air vent, water discharge and pressures in the conduit were measured. These tests were run at four different gate closure times (continuous gate closure) as depicted in Table 1.

The transient gate closing simulations were also conducted at three different water levels for each of the four above-mentioned gate closure times. The water levels are summarised in Table 2.

The commissioning water level corresponds to the water level that was measured in the field during the commissioning test of the Berg River Dam in June 2008.

The level where vortices started to form in the water tank (vortex water level) was determined to be 227.12 masl for the middle gates on the intake tower. The lower water level mentioned in Table 2 was taken halfway between the commission test water level and the vortex water level.

EVALUATION AND DISCUSSION OF RESULTS

Validation of the Berg River Dam model

The field measurements at the dam were done intermittently with a hand-held anemometer which recorded only velocity and not direction. The observer commented that at about 40% gate opening the air flow was surging at 10 cycles per minute. Since the air direction was not recorded continuously, it could be at this stage that intermittent in- and outflow occurred in the air vent. The field recordings were therefore not ideal, and more rigorous recordings were unfortunately not possible for inclusion in this study, since TCTA and BRC decided that commissioning tests should not be repeated. The reason for this decision was because the tests could expose the dam and pertinent structures to unnecessary damaging forces; in addition it must be borne in mind that the emergency gate will probably never be used again in the lifetime of the dam.

Tests performed on as-built outlet conduit model

Possible vortex air entrainment upstream of the emergency gate

In a report on the commissioning test on the Berg River Dam (Shand 2008), vortex formation is cited as the most likely cause of the air reversal flow.

To test for vortex formation, the water in the wet well was stirred while the emergency gate was 100% open and the water level was kept at the commissioning water level. However, no air entraining vortices could be induced in the wet well at this water level.

The water level was lowered until air entraining vortices formed in the wet well. The highest level at which vortices formed was found to be at 227.12 masl. At this level all the air entrained into the outlet through the vortices travelled down the conduit and was released at the downstream end of the conduit. Vortex formation was therefore not the cause of the air reversal flow in the air vent, as observed in the field during the emergency valve commissioning tests.

Table 2 Water levels

Water level name	Prototype (masl)	Model (m) (Datum = bottom of outlet conduit at upstream end)
Full supply water level (level of dam spillway)	250.0	3.8
Commissioning test water level (June 2008)	237.5	2.9
Lower water level	232.32	2.5

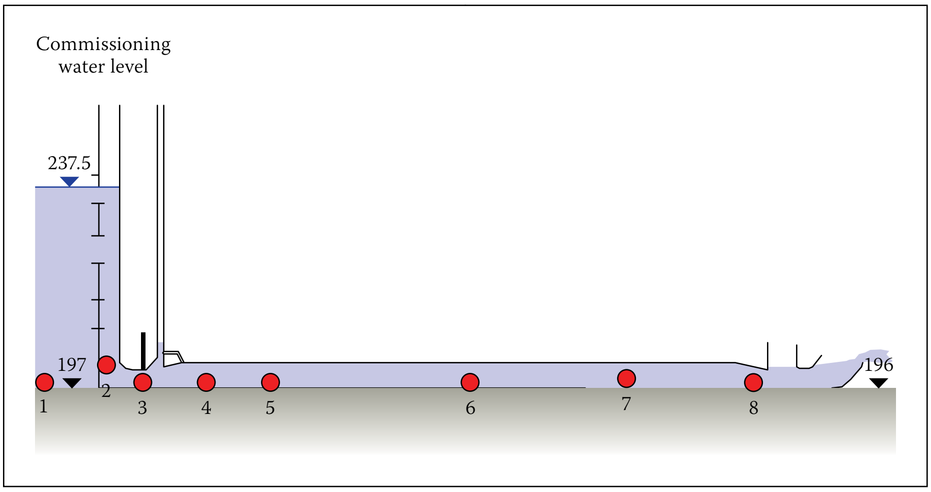

Figure 8 Location of pressure transducers (shown in elevation)

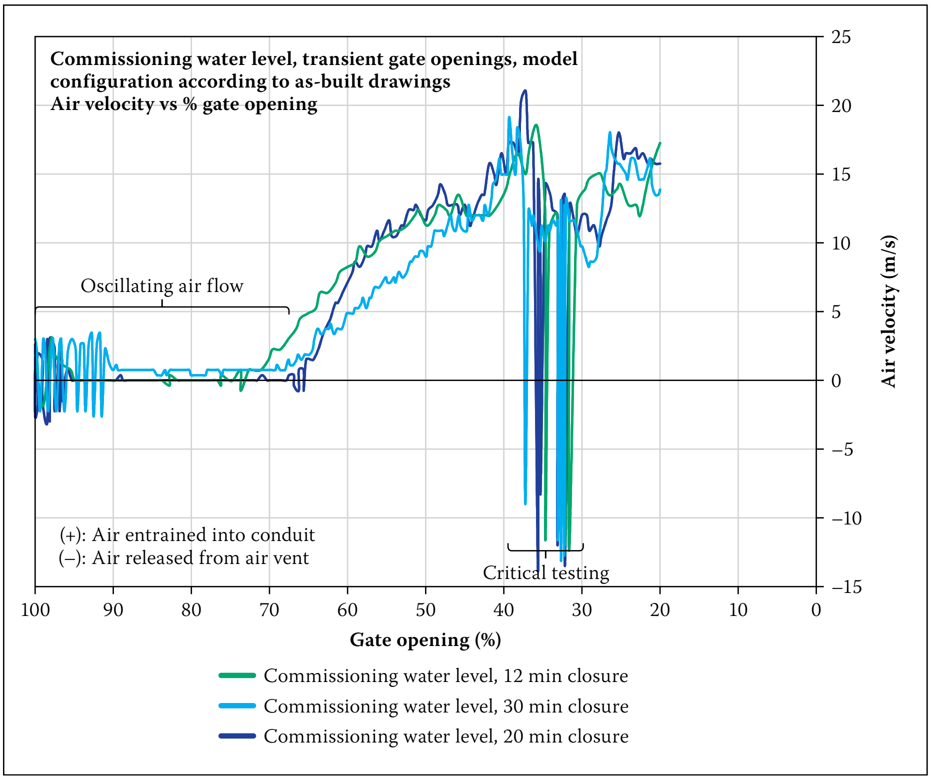

Figure 9 Air velocity in air vent vs gate opening for different gate closure times (commissioning water level, transient gate, as-built, velocities converted to prototype values)

Tests to search for other causes of reverse air flow in air vent

Impact of gate closure time

It was observed that air was released from the air vent for the transient gate simulations (emergency gate closing continuously). The effect of the different gate closure times/rates on the air velocity in the air vent for the commissioning water level is illustrated in Figure 9. Air was released for gate openings between 37% and 32%, irrespective of the specific gate closure time under evaluation. For gate openings outside the latter gate opening stage, air was entrained into the air vent for all gate closure times investigated.

Figure 10 illustrates the effect of the various gate closure times on the pressures just upstream of the radial gate chamber (pressure transducer number 7) for the commissioning water level conducted on the as-built outlet conduit.

A steep drop in pressure occurred for gate openings between 37% and 33%, irrespective of the gate closure time. The steep drop in pressure occurred at the same time as when air blowback occurred in the air vent.

It was concluded that the air velocity in the air vent was independent of the time of closure of the emergency gate.

Conclusions from tests on as-built model outlet

From the tests performed on the as-built model of the Berg River Dam outlet works it was concluded that the air flow in the air vent was predominantly into the conduit (downwards) during emergency gate closures. However, rapid reverse air flow occurred between gate openings of 37% and 25%.

Air was essentially drawn into the conduit through the air vent and was dragged downstream either insufflated in the flow or above the water. At the downstream end of the conduit the outflow of air was restricted by the tapered soffit section of the radial gate chamber. An unstable hydraulic jump formed in the outlet conduit as a result of the transition from the pressurised flow to free surface flow. Entrapment of air occurred between the unstable hydraulic jump and slanting roof of the radial gate section. The entrapped air in the conduit was pressurised due to the upstream and downstream water seals (see Figure 11(a)).

Between 37% and 32% gate openings the jump intermittently broke contact with the roof to the conduit (due to the reduced discharged and increasing air pressure from behind the jump), and pressurised air in the conduit from downstream of the point where

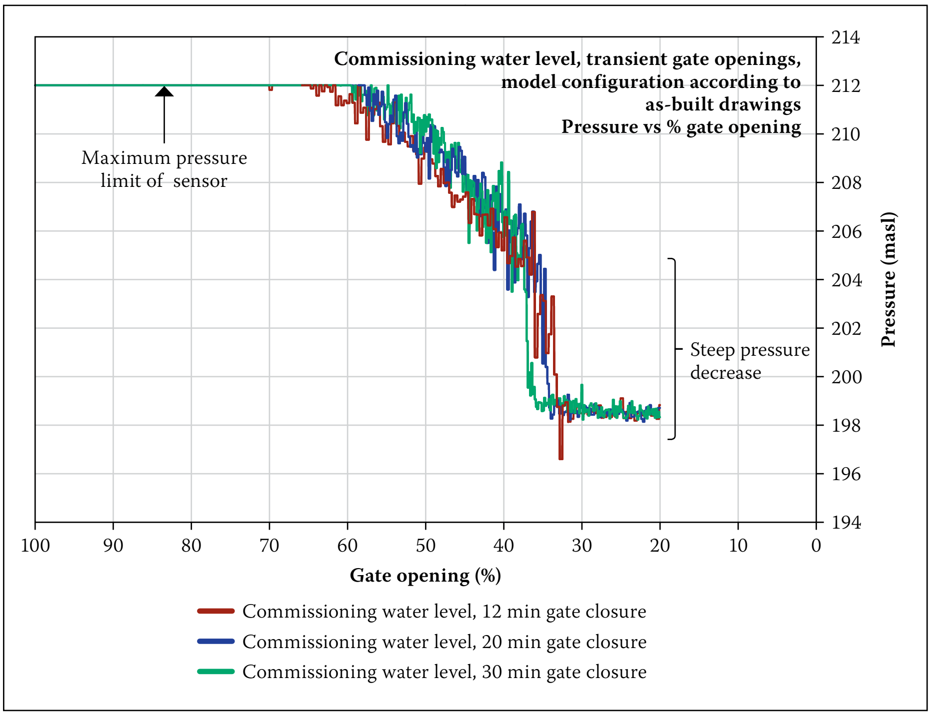

Figure 10 Effect of gate closure time on pressure at end (location 7) of conduit (commissioning water level – prototype values)

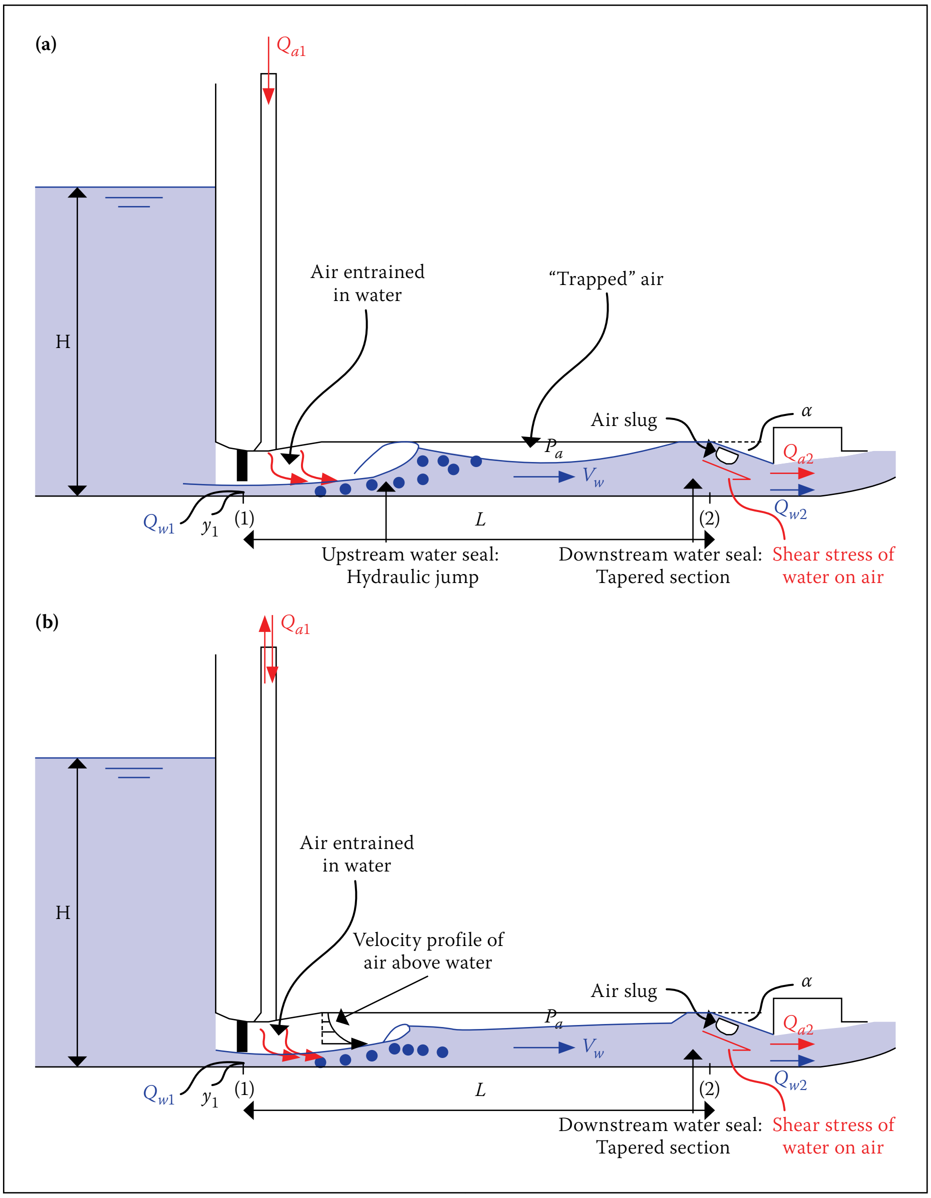

Figure 11 Reason for air blow-back: (a) "trapped" air, and (b) air released via air vent

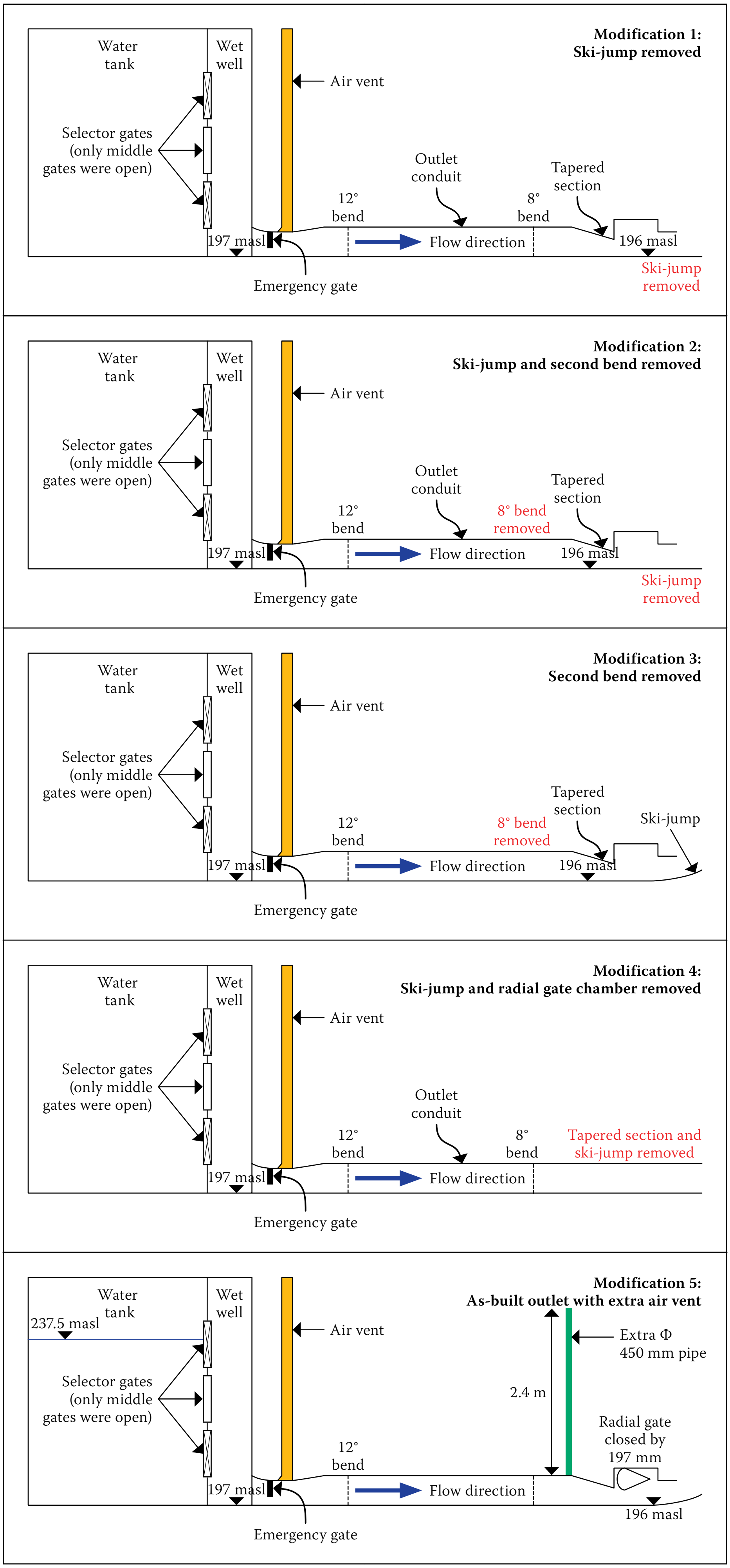

Figure 12 Modified model configurations

the jump broke contact with the roof was released back upstream and out the air vent (see Figure 11(b)). The air velocity in the air vent was the highest over this period and changed direction rapidly as pulses of air were expelled while the unstable hydraulic jump was moving downstream. The air flow problem of the Berg River Dam was therefore determined to be one of intermittent **air blowback** at a specific stage of the gate opening.

Based on the above, the most probable reason for blowback is the constriction of flow at the radial gate chamber.

Tests performed on modified model configurations

Modified model configurations

In order to confirm the cause of the air blowback and to investigate possible solutions, a number of tests were performed on modified outlet model configurations. Although the expected cause of the blowback was considered to be the flow constriction caused by the radial gate chamber, the ski-jump and the second bend in the conduit were also identified as components possibly having an effect on the flow. Figure 12 shows the configurations of the modified model configurations tested.

Removal of ski-jump and second bend

It was found that the removal of the ski-jump and the second bend had very little effect on the flow in the conduit. The results of the tests on Modifications 1, 2 and 3 are presented in Figure 12 and show very similar trends to those on the as-built outlet.

Removal of radial gate chamber

Removal of the radial gate chamber was found to have a significant effect on the flow patterns in the conduit, and eliminated the air blowback.

The air velocity and pressures versus gate opening graphs for the five modifications are shown in Figure 13 and Figure 14 respectively.

Without the radial gate constriction (modification 4), the air velocity in the air vent increased with increasing gate opening, no backflow occurred and air flow remained positive (i.e. air entrainment prevailed) for all stages of gate opening. The pressures observed for modification 4 (at location 7) in the conduit are also much lower with less variation/fluctuation than those experienced on the other modifications, which included the radial gate chamber. This is because free-surface flow occurred throughout the conduit for all gate openings, instead of partially pressurised flow which occurred when the outlet was constricted (as-built outlet and modifications 1, 2, 3 and 5).

Figure 15 shows a schematic comparison between the observed flow in the as-built outlet and the modified outlet with the aid of sketches at gate openings of 100% and 37%.

Provision of additional air vent at the radial gate constriction

Once it was confirmed that the radial gate constriction was the cause for air blowback, it was suggested that an additional air vent placed immediately upstream of the radial gate constriction may solve/reduce the air blowback problem. If effective, this would possibly be a practical retro-fit solution for the existing Berg River Dam.

An additional 450 mm (prototype) diameter air vent was fitted directly onto the as-built conduit. It was found that the additional air vent was ineffective in reducing the blowback effect, and the air flow and pressure results were similar to those of the as-built tests and other modifications which included the radial gate constriction as seen in Figure 13 and Figure 14 respectively. During the test water was trapped in the additional air vent and blocked the free release of air. For the critical gate openings of 37% to 25% (while air blowback was experienced in the upstream air vent), an air-water mixture was intermittently expelled from the extra air vent in an explosive fountain display, shooting water approximately 30 m (prototype) into the air above the top of the vent.

Conclusions from tests on modified model configurations

The test results indicated that the cause of the air blowback is the constriction at the radial gate chamber at the downstream end of the conduit. When the flow is not constricted there, free-surface flow occurred throughout the conduit for all openings of the emergency gate, and the air blowback in the air vent was eliminated.

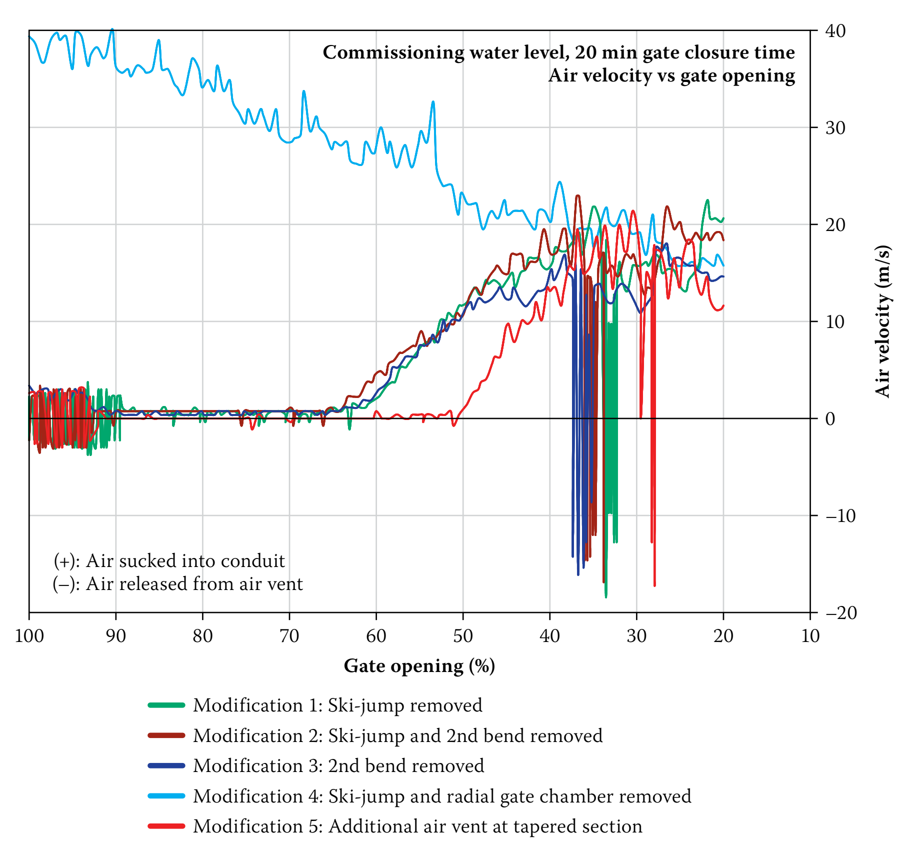

Figure 13 Air velocity in air vent versus gate opening for modified outlet conduit

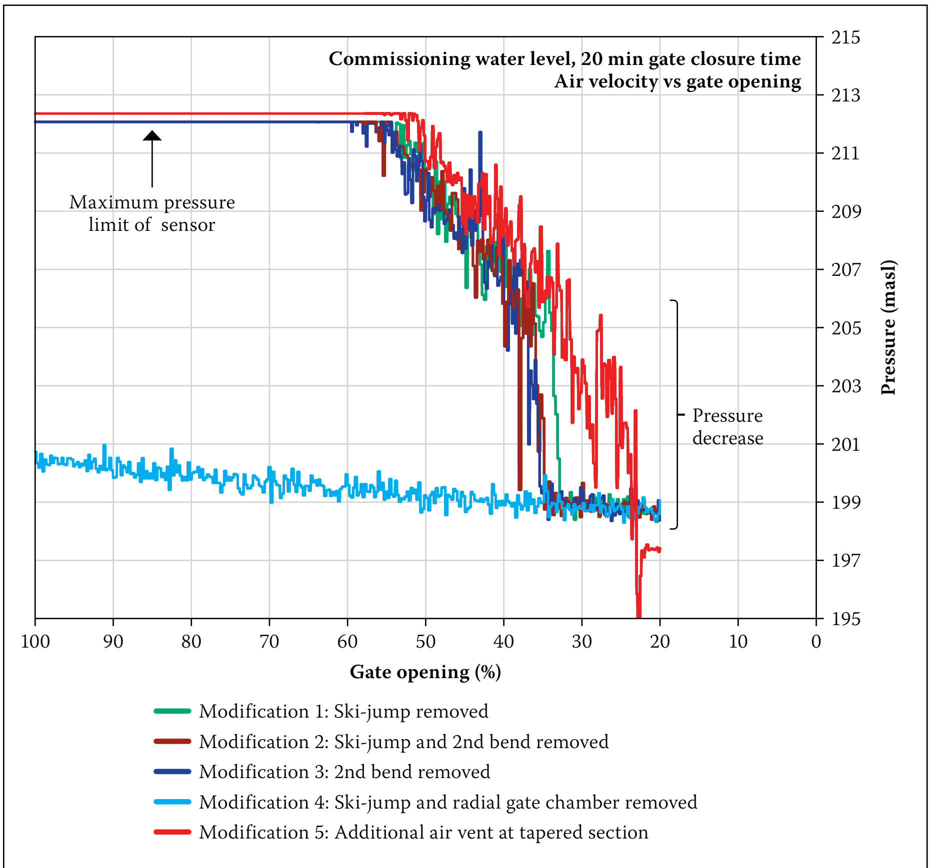

Figure 14 Pressure upstream of radial gate chamber (at location 7) versus gate opening for five modifications to the outlet conduit

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The main conclusion drawn from the physical model tests on the air flow problem in the air vent of the Berg River Dam outlet conduit is that air blowback occurred at a specific gate opening range (25% to 37%) of the emergency gate due to the constriction in the outlet conduit at its downstream end. During the stages of valve opening outside the latter opening range only air inflow into the air vent was observed, which is contrary to what was subjectively observed during the field observations during commissioning testing of the emergency valve.

During the stages of air inflow into the air vent, air was essentially drawn into the conduit through the air vent due to high water velocity in the conduit, which dragged

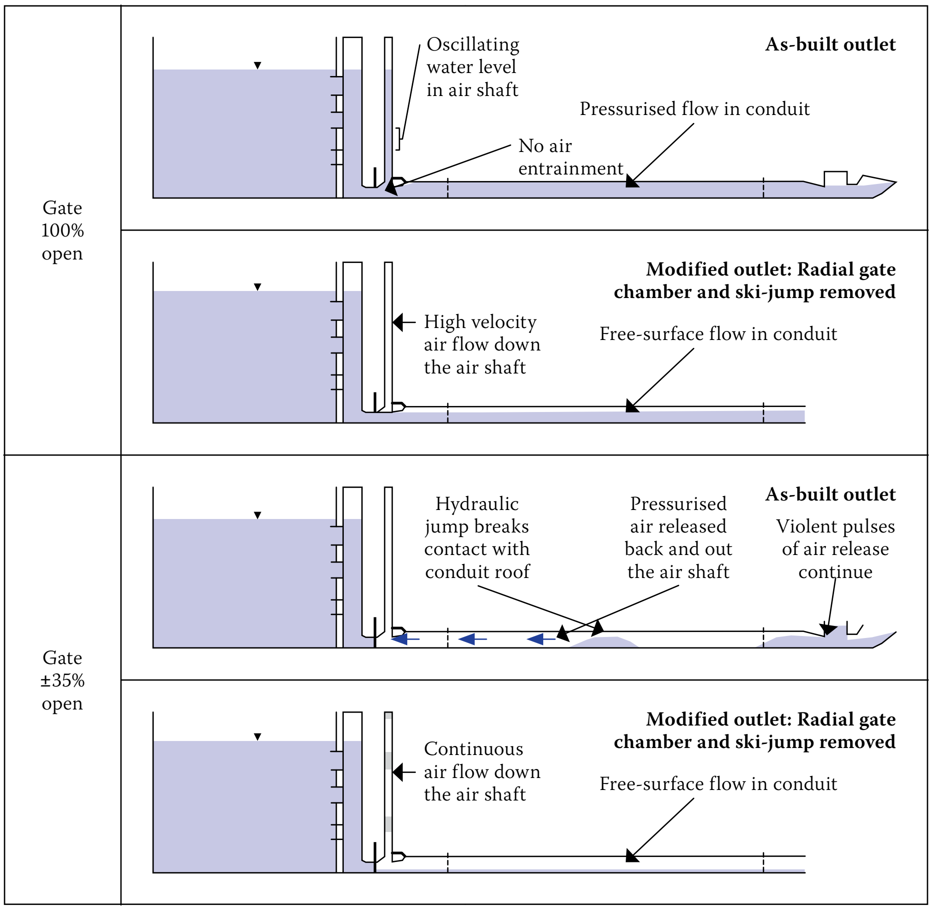

Figure 15 Sketches of flow patterns for as-built conduit and modified conduit with radial gate and ski-jump removed for 100% and 37% gate opening

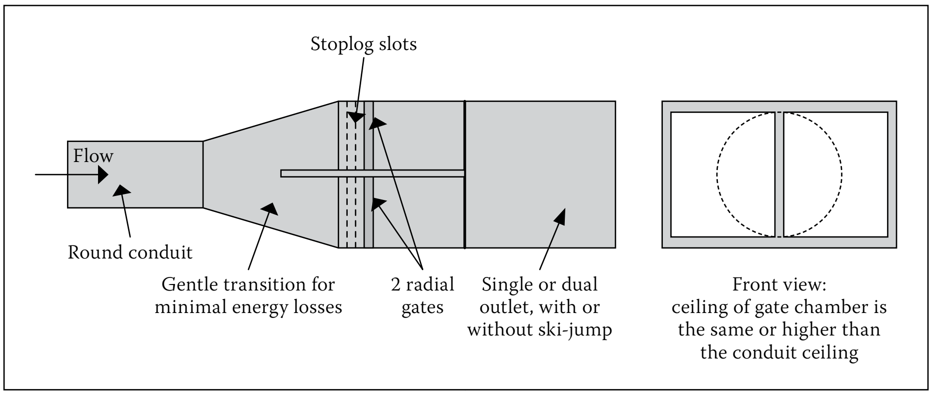

Figure 16 Possible radial gate configuration at the downstream end of an outlet conduit to prevent air blowback in the air vent of the conduit

air downstream by insufflation into the water and above the water surface by shear stress of the water flow at the water-air interface. At the downstream end of the conduit the outflow of air was constricted by the tapered section of the radial gate chamber (ceiling of conduit sloping downwards), resulting in pressurisation of the air in the conduit. This pressure caused air blowback through the air vent when the upstream hydraulic jump broke contact with the roof of the conduit.

Tests performed with the radial gate constriction removed (modification 4) confirmed that it had been the cause of the blowback experienced in the latter tests. These tests showed free-surface flow throughout the valve closure operation of the emergency gate and no reverse air flow/blowback occurred – only air entrainment into the air vent occurred. Tests on the other modified model configurations (modification 1, 2 and 3) confirmed that removal of the ski-jump and the second bend (8°) had little effect on the results. An additional 450 mm air vent was installed directly upstream of the constriction (modification 4). Test results on this modification indicated it to be ineffective in reducing the air blowback.

Air entrainment due to vortices in the water did not occur in the wet well (even with manual stirring of the water in the wet well) for tests performed at the commissioning water level. Air blowback did not occur at the critical reservoir level at which air commenced to be entrained via a vortex in the wet well water, i.e. at a water level in the wet well of 227.12 masl.

It was found that the air velocity in the air vent was independent of the gate closure time, but increased with an increase in water head.

Recommendations

Based on the findings of this physical model study on the air flow problem in the air vent of the Berg River Dam's conduit outlet, certain recommendations can be presented.

To prevent air blowback in the air vents of high-head outlets such as that of the Berg River Dam, it is recommended that free water flow should always be ensured for all conditions over the entire length of the outlet conduit, and water and air flow should never be constricted by any structure or mechanism at the downstream end of the conduit, especially not at the soffit of the conduit.

For an outlet design such as that of the Berg River Dam (even with the constriction at the radial gate chamber removed) a potential air blowback problem could occur if the radial gate should fail in a partially closed position. A possible solution in such a case would be a dual radial gate system in which each gate has the capacity for the full design discharge (Figure 16). Under normal operation one gate could be used while the other gate remains closed. In the case of failure of a gate in a partially closed position, the other gate can be fully opened to allow un-constricted flow before the emergency gate is closed.

GUIDELINES FOR THE DESIGN OF FUTURE BOTTOM OUTLETS

The following design guidelines should be adhered to in future designs to prevent air blowback:

- Bottom outlets should be designed to ensure free-surface flow conditions under all probable flow conditions, and the formation of hydraulic jumps in the conduit should be avoided (USACE 1997).
- Air entrapment at all changes in cross section should be avoided by matching tunnel ceiling heights rather than inverts (USACE 1997).
- The upstream movement of air which can cause possible blowback problems due to buoyancy forces should be avoided by keeping the slope of the outlet conduit as flat as possible (Falvey 1980).
- The outlet conduit downstream of the emergency gate should be as short as possible, and straight.

- The crest height of a ski-jump should not be so high that it could cause submergence of the conduit under low-flow conditions.
- The flow in an outlet conduit should not be restricted for any foreseeable flow condition. The case of a radial gate failing in a partially closed position is a particular scenario that would cause a constriction which may cause a severe restriction of the flow, possibly leading to dangerous air blowback during emergency gate closures. (A possible configuration to prevent blowback in this case is discussed in the section called "Tests performed on as-built outlet conduit model").
- Large-scale hydraulic models (greater than 1:20) should be used in the design process for partially full-flow outlet conduits to minimise scale effects and to readily observe the detailed flow behaviour (Speerli 1999; WRC 2012).

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REFERENCES

Basson, G R 2011. Commissioning test of Berg River Dam in 2008. (Interview with A Bosman on 17 February 2011.)

Falvey, H T 1980. *Air-water flow in hydraulic structures.* Engineering Monograph No 41. Denver, CO: Water and Power Resources Service.

Lowe, F C 1944. *Hydraulic model studies for the glory-hole spillways at Owyhee Dam – Owyhee Project, Oregon–Idaho.* Denver, CO: US Department of the Interior – Bureau of Reclamation.

Shand, M 2008. *Berg River Dam emergency gate commissioning release of air.* Cape Town: Ninham Shand.

Speerli, J 1999. *Air entrainment of free-surface tunnel flow.* Switzerland: Swiss Federal Institute of Technology.

TCTA (Trans-Caledon Tunnel Authority) 2003. *Berg River Project hydraulic model testing of the outlet works model. Scale 1:20.* South Africa: Sinotech cc.

TCTA (Trans-Caledon Tunnel Authority) 2008. Berg River Dam: Designed with rivers in mind. *The Water Wheel*, 33–37.

USACE (United States Army Corps of Engineers) 1980. *Hydraulic design of reservoir outlet structures.* Report EM 1110-2-1602. Washington, DC: USACE.

USACE (United States Army Corps of Engineering) 1997. *Engineering and design – Tunnels and shafts in rock.* Engineering Manual No 1110-2-2901. Washington, DC: USACE.

Vos, A 2011. *Unsteady flow conditions at dam bottom outlet works due to air entrainment during gate closure: Berg River Dam model.* Stellenbosch: University of Stellenbosch. Available at: http://scholar.sun.ac.za/handle/10019.1/71850.

Webber, N 1971. *Fluid Mechanics for Civil Engineers,* SI ed. London: Chapman and Hall.

WRC (Water Research Commission) 2012. *Investigation of unsteady flow conditions at dam bottom outlet works due to air entrainment during gate closure. Volume I: Physical modelling.* Report TT528/12. Stellenbosch: University of Stellenbosch.